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Hydrodynamical impact on biogeochemical processes in aquatic sediments

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Abstract

Boundary layer flow characteristics and sediment permeability control pathways and magnitude of material exchange in the surface layer of aquatic sediments. In fine-grained cohesive beds, bottom currents and sediment microtopography shape the diffusive boundary layer and locally produce areas where the interfacial solute fluxes are increased or reduced. Where sediment permeabilities exceed 10^{-12} m^2, advective pore water flows driven by boundary flow–topography interaction dominate the sediment–water exchange of matter, with transport rates that exceed those of molecular diffusion by two orders of magnitude and more. The curved paths of the advective pore flows through the surface layers of such sandy beds generate complex three-dimensional biogeochemical patterns with extreme spatial and temporal variability ranging from millimeters to decimeters and seconds to seasons. High filtration rates, a bacterial community firmly attached to the mineral grains, rapidly changing biogeochemical zonations and winnowing of the sediment surface layers by frequent resuspension convert these beds into effective biocatalytical filter systems.

Transport mechanisms at the sediment–water interface

In shallow aquatic environments, the sediment bed is the most important site for accumulation, storage and biogeochemical transformation of organic matter and contaminants (Canfield et al., 1993; Wainright et al., 1992; Villar et al., 1999). The extent to which the sedimentary processes are linked to the overlying water column is determined by transport mechanisms that carry particulate and dissolved substances into and out of the bed (Berner, 1976; Vanrees et al., 1996). In most aquatic environments, the most important transport processes are molecular diffusion, gravitational settling, bioturbation and burrow irrigation (bioirrigation), pore water advection and burial due to lateral sediment transport (Aller, 1982; Shum & Sundby, 1996; Vaughn & Hakenkamp, 2001). All these mechanisms are strongly affected by boundary layer flows making water currents, surface gravity waves and turbulence dominant factors controlling benthic–pelagic coupling.

Boundary flows and diffusive sediment–water exchange

Where the boundary flows are weak, fine-grained sediments can accumulate producing deposits with organic matter and solute concentrations that exceed those in the overlying water column by far (Berner, 1980; Ignatieva, 1996). Due to the resulting concentration gradients and the relatively low hydraulic conductivity of these deposits, molecular diffusion in such beds usually is the most important mechanism for the transport of dissolved substances across the sediment–water interface. In such environments, the boundary layer hydrodynamics govern the biogeochemistry of the sediment surface layers by controlling the solute concentration gradients at the sediment water interface (Jørgensen, 1994; Golosov & Ignatieva, 1999). These gradients are not only shaped by the characteristics of the boundary layer flow (e.g., laminar or turbulent) but also by the interaction of the flow with the microtopography of the sediment. Jørgensen & Des Marais (1990) observed the compression and dilatation of

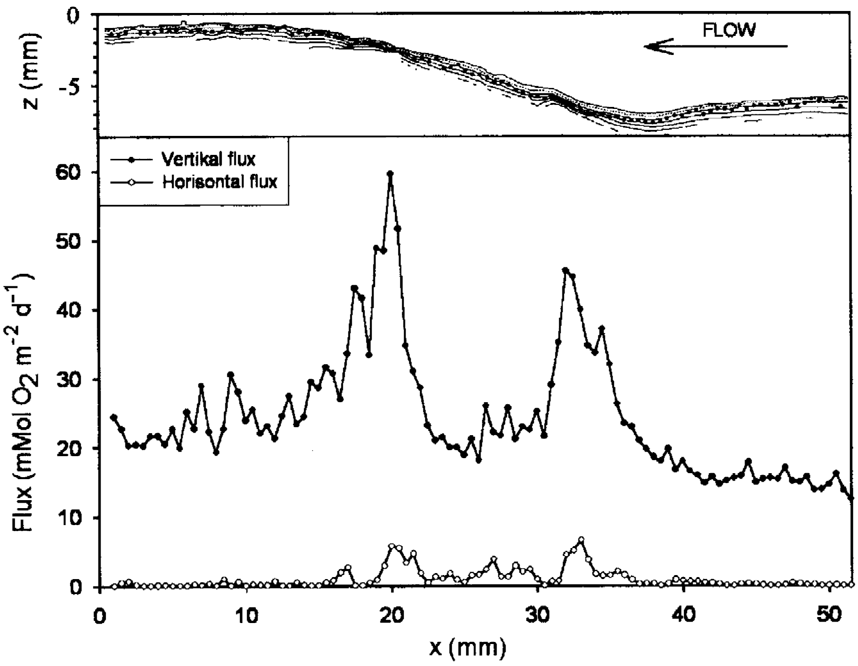

Figure 1. Upper pane: cross-section of a fine grained sediment that was inhabited by oligochaetes (interface indicated by dotted line) and the oxygen concentration isolines that are shaped by the interaction of the microtopography, hotspots and boundary layer flow. The isolines were derived from oxygen profiles measured with a microsensor at a spatial resolution of 250 and 100 μm in horizontal and vertical direction, respectively. The isolines reveal compression of the diffusive boundary layer (DBL) and enhanced vertical and horizontal oxygen flux (lower pane) at microtopography and two hotspots (at $x = 20$ mm and $x = 32$ mm). The latter were caused by fresh faecal pellets deposited on the surface by oligochaetes. The elevated flux between 10 and 30 mm relative to the flux between 40 and 50 mm can be attributed to the compression of the DBL. Median grain size 6.3 μm, permeability $k = 1.5\times 10^{-13}$ m^2; porosity = 0.8, organic content = 2.9%, shear velocity $u* = 0.09$ cm s^{-1}.

oxygen concentration isolines due to locally accelerating or decelerating contour flows at microtopography of a microbial mat. In their recent microscale studies of oxygen distribution at the surface of a silty bioturbated sediment, Røy et al. (2002) demonstrated that flow–microtopography interaction affects also the diffusive boundary layer and oxygen flux in fine-grained marine sediments. At sub-millimetre scale, the sediment surface appears as a three-dimensional structure where the concentration gradients that loosely follow the topography support fluxes not only in vertical but also in horizontal direction (see Fig. 1). A one-dimensional measuring approach may underestimate oxygen flux in such settings by 5–15% revealing the importance of flow, topography and the ensuing three-dimensional nature of the sediment water exchange.

Advective filtering in permeable sediments exposed to flow

The importance of boundary flows for the metabolic activities in the sediment increases with increasing intensity of the flow near the sediment–water interface (Berninger & Huettel, 1997; Migne & Davoult, 1998). In river and shallow coastal environments, strong bottom currents frequently resuspend and winnow the sediment resulting in coarse-grained beds with relatively high hydraulic conductivities and low content of organic matter (Li & Amos, 1999). Nevertheless, such sediments can have oxygen consumption rates similar to those recorded for fine-grained beds rich in organic matter suggesting that these beds efficiently mineralise organic material originating from the overlying water column (Andersen & Helder, 1987; Lohse et al., 1996). However, strong currents and turbulence exceeding the settling velocities of organic matter and fine particles by far require other processes than gravitational settling for the uptake of such substances into the sediments. The boundary layer hydrodynam-

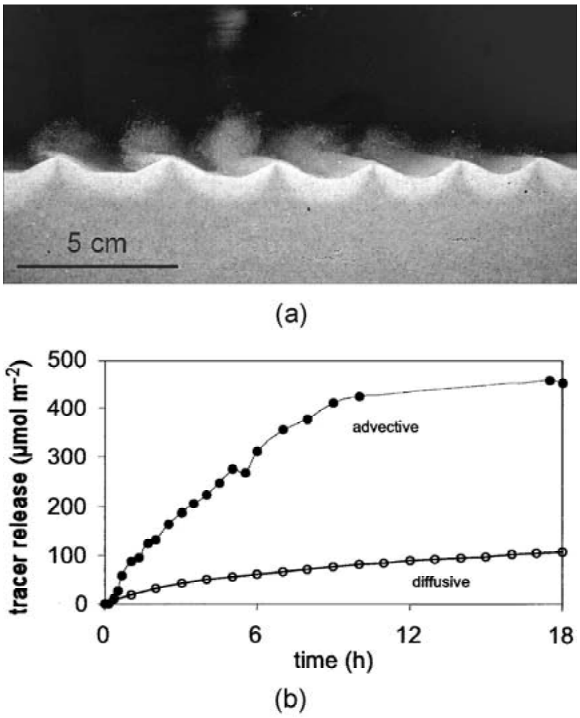

Figure 2. Upper pane: advective pore water exchange due to oscillating boundary currents interacting with ripple topography generated by waves. Stained pore water is released to the water column at the ripple crests, while unstained water intrudes the sediment in the ripple troughs. Experimental settings: median grain size, 250 μm; $k = 2.9\times10^{-11}$ m^2; water depth in wave tank, 20 cm; wave amplitude, 10 cm; wavelength, 120 cm; av. u^* = 0.12 cm s^{-1}; filtration rate, 90 L m^{2}d^{-1}. Lower pane: comparison of advective and diffusive release of solute tracer from the same sediment under stagnant flow conditions and exposed to the waves. Advective release due to waves in this case increased solute flux by factor 10 relative to diffusion.

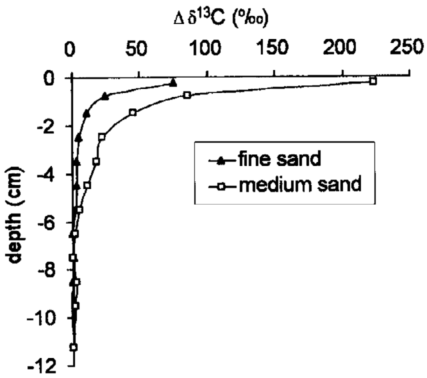

Figure 3. Results of an *in situ* experiment on transport of ^{13}C-labelled *Ditylum brightwellii* diatom cells into North Sea sediments of different grain size and permeability. Fine sand: $k = 2.4\times10^{-12}$ m^2; penetration time, 32 h; medium sand, $k = 22.6\times10^{-12}$m^2; penetration time, 20 h. Interfacial water flows carried labeled diatoms down to 3 cm in the fine sand and down to 6 cm in the medium sand. In the latter this transport distance was covered in less than 1 day.

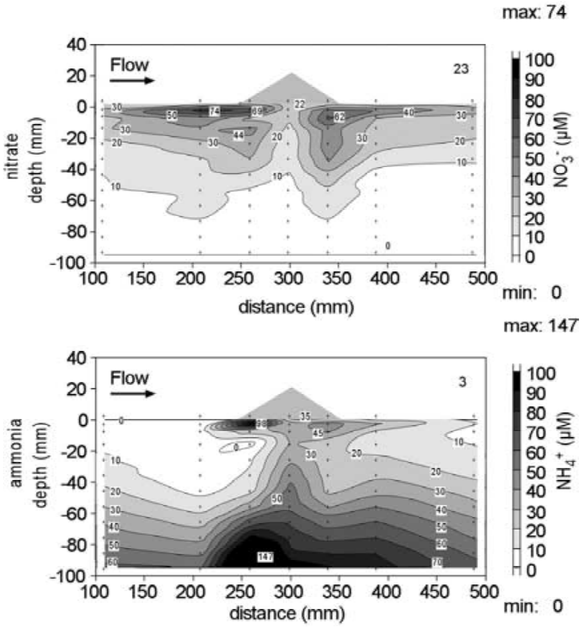

Figure 4. Zones of enhanced nitrification are generated up- and downstream of protruding surface structures (in this case a small mound of 2.5 cm height, upper pane), while pore water rich in ammonia is drawn to the surface underneath the protrusion creating steep gradients between aerobic and anaerobic sediment zones (lower pane). Here ammonium-oxidizing bacteria find ideal growing conditions. Likewise metals are affected by the advective pore water flows. Dissolved ferrous iron and dissolved manganese are drawn from deeper anoxic sediment layers to the surface. The upwelling pore water flows, thus, create a pathway of reduced metals through the oxidized surface layer of the sediment permitting the release of these substances to the water column. Pollutants can be released from such sediments in the same manner. Median grain size 350 μm, permeability $k = 5.1\times10^{-11}$ m^2; porosity = 0.4; organic content = 0.2%; shear velocity u^* = 0.38 cm s^{-1}. (Modified after Huettel, M., W. Ziebis, S. Forster & G. W. Luther, 1998. Advective transport affecting metal and nutrient distributions and interfacial fluxes in permeable sediments. Geochim. Cosmochim. Acta, 62(4): 613–631.)

ics again are the key factor controlling the transfer of matter into these sediments. In such high-energy environments, advective pore water flows and lateral sediment transport control the transfer of matter into the permeable bed.

Interfacial advective flows are driven by small lateral pressure gradients (ca. 1–3 Pa cm^{-1}) that result from the interaction of unidirectional or oscillating boundary layer flows with sediment topography (Huettel & Gust, 1992). Obstruction of the flow by protruding structures causes local increase of pressure that forces water and suspended particles into porous sediments, while the acceleration of flow when passing over these protrusions results in a pressure

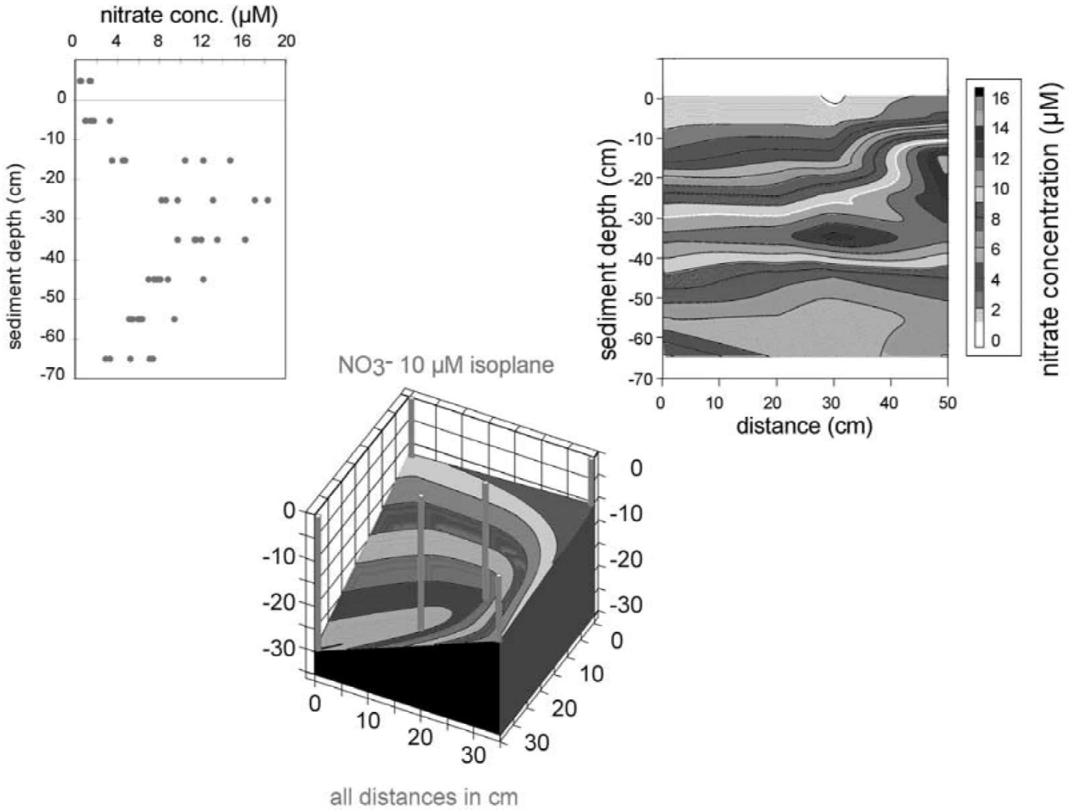

Figure 5. The same set of nitrate pore water profiles originating from permeable carbonate sediment (Kaneohe Bay/Oahu, permeability $k = 5\times10^{-11}$ to 9×10^{-11} m^2) depicted in one- (upper pane), two-(middle pane), and three-dimensional (lower pane) plots. The pore water samples were taken from a sediment volume with 35 × 35 cm surface area and 70 cm depth using the seepers represented by the grey vertical lines in the lower pane of the graph. In permeable sediments the variation of concentrations between individual vertical profiles measured in close proximity may be caused by the complex three-dimensional nature of the biogeochemical zonation. By collecting horizontal spatial information with the vertical profiles, this three-dimensional structure can be shown.

decrease that draws pore water from the sediment (Savant et al., 1987; Thibodeaux & Boyle., 1987; Huettel et al., 1996) (see Fig. 2). In typical coastal settings this transport reaches to approximately 15 cm sediment depths. Because there is no river or sea bed that is perfectly smooth, all natural sediments with a permeability exceeding 10^{-12} m^2 function as effective filter systems when exposed to boundary layer flow.

The ecological relevance of the interfacial advective water flows is linked to the transport of reactive materials into permeable sediments. Laboratory and *in situ* experiments showed that phytoplankton cells, bacteria and organic detritus particles are transported several centimeters into the sediment within 12–24 h (Pilditch et al., 1998; Huettel & Rusch, 2000; Rusch et al., 2001) (see Fig. 3). This process causes rapid particulate matter uptake in environments where strong boundary currents prevent the gravitational deposition of organic matter.

Concurrent with the transport of organic particles into the bed, water rich in oxygen and other electron acceptors (e.g., nitrate, sulfate) is forced into the sediment and, because the fluid experiences less friction than the particulate matter, passes through the layers where the intruding particles accumulate within the bed (Huettel & Rusch, 2000). The pore water flow field associated with sediment topography dictates a directed flow from the area of intrusion to the release zone providing an efficient exchange mechanism for pore water and dissolved metabolites. More than 90% of the bacterial cells in sandy sediments are attached to the mineral grains (Rusch et al., 2001). When water rich in organic matter and electron acceptors is flushed through sand beds, the bacterial community converts

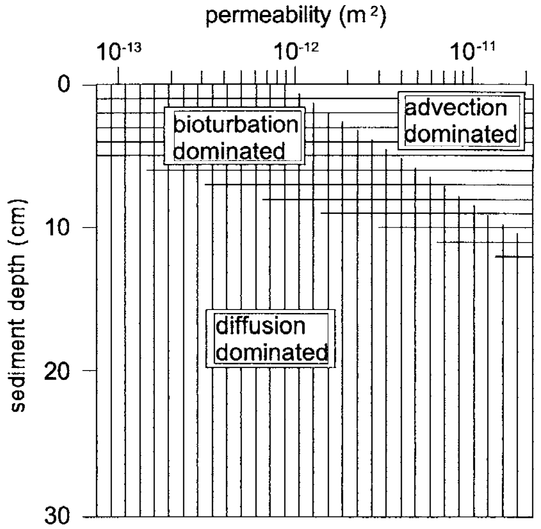

Figure 6. The permeability and depth ranges of the main transport mechanisms in aquatic environments. The zone where bioturbation is dominant is depicted for marine coastal environments. (Modified after Huettel & Gust, 1992. Impact of bioroughness on interfacial solute exchange in permeable sediments. Mar. Ecol. Progr. Ser. 89(23), 253–267.)

these beds into efficient biocatalytical filters (see Fig. 4).

Spatial and temporal heterogeneity in sedimentary biogeochemical processes due to boundary flow–topography interaction

Because in natural environments sediment topography as well as the boundary layer flow characteristics change on time scales ranging from seconds to seasons, the fast advective transport of particles and fluid caused by the topography–flow interaction generates a rapidly changing biogeochemical zonation of complex three-dimensional structure (Huettel et al., 1998) (see Fig. 5). These rapid spatial and temporal changes further enhance the biocatalytical activity of permeable aquatic sediments and accelerate the transformation of matter in these beds (Aller, 1994). A low content of reactive materials in such beds, thus, cannot be interpreted as low metabolic activity but rather is the consequence of rapid turnover and high exchange rates.

Conclusions

The hydrodynamical boundary flow conditions and the permeability of the sediment define whether diffusion or advection dominates the exchange of substances between aquatic sediments and the overlying water column. When sediment permeability exceeds 10^{-12} m^2, advective transport surpasses diffusion (see Fig. 6). In natural environments, this picture is complicated by the activity of benthic meio- and macrofauna organisms that enhance interfacial transport of solutes and particles by bioturbation and bioirrigation. In coastal permeable beds, this biological transport locally can be as efficient as advective exchange; however, the biological activity is also controlled by the boundary hydrodynamics (e.g., due to supply of oxygen or food particles). Exchange of solutes and particles in aquatic environments is controlled by the hydrodynamic conditions at the sediment–water interface, and measurements attempting to quantify the interfacial exchange have to take the variability of the boundary flows and sediment permeability into account.

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